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Author(s): Richard A. Kalnicky

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CLIMATIC CHANGE SINCE 1950*

RICHARD A. KALNICKY

ABSTRACT. The mean temperature for the Northern Hemisphere had a warming trend from 1890 to 1950 and a cooling trend since 1950. The eastern and central United States had colder temperatures in 1961–1970 than in 1931–1960. The temperature changes were associated with an adjustment of hemispheric circulation from more frequent zonal flow between 1900 and 1950 to more frequent meridional flow since 1950. Regional variations in magnitude and direction of the change were largely related to position in relation to the upper air westerly wave pattern. Time series of individual circulation indices tend to resemble the step function model of climatic change. **KEY WORDS:** *Atmospheric circulation, Climatic change, Step function model, Temperature change, Westerly wave pattern.*

RELIABLE instrumental temperature records encompassing at least the last hundred years are available for populated areas in the Northern Hemisphere.¹ Analysis of these

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Mr. Kalnicky is a doctoral candidate in the Department of Geography at the University of Wisconsin in Madison, WI 53706.

* Prof. W. M. Wendland helped formulate the research problem, and his criticisms concerning the first draft of the manuscript were very helpful; Prof. E. Wahl suggested the data source; T. J. Blasing and Prof. J. Kutzbach assisted in the computer analysis; Prof. J. Knox provided helpful criticisms and encouragement and information concerning submission of the manuscript; computer funds were provided by the University of Wisconsin Computer Center Research Committee; illustrations were prepared by the University of Wisconsin Cartographic Laboratory; the research was supported in part by National Science Foundation grant No. GA-10651X to the Center for Climatic Research at the University of Wisconsin.

¹ Continuous records for the last hundred years exist for much of the western United States. In the eastern United States a few continuous series and old military fort records extend back 150 years. The New Haven, Connecticut, record, which began about 1780, is the longest continuous record in the United States. Continuous data for the last 200 years exist for a few central European stations, and some Scandinavian stations have about 150 years of data. Some of the longest European data consist of 250 years of record at Zwanenburg-Utrecht-De Bilt, Netherlands, in A. Labrign, *The Climate of the Netherlands during the Last Two and a Half Centuries*, Koninklijk Nederlandsch Meteorologisch Instituut No. 102, Mededeelingen and Verhandelingen 49 ('s-Gravenhage, Netherlands:

records by many investigators indicates that a substantial change in many local, regional, and hemispheric temperature trends occurred near 1950.² One of the purposes of this study is to reexamine the hemispheric trend over the past hundred years. The magnitude and geographical variation of recent temperature changes in the United States are discussed in more detail.

Temperatures near the earth's surface are highly related to the atmospheric circulation. The maximum daily temperature at a station is a function of the air mass located over the station.³ Circulation patterns dictate which air masses are advected into a particular location. The frequency distribution of station temperatures, which, averaged together, give the mean temperature, is associated in this manner with

Rijksuitgeverij, 1945), and almost 300 years for central England, in Gordon Manley, "The Mean Temperature of Central England 1698–1952," *Quarterly Journal of the Royal Meteorological Society*, Vol. 79 (1953), pp. 242–61.

² These investigations include J. M. Mitchell, Jr., "Recent Secular Changes of Global Temperature," *Annals*, New York Academy of Sciences, Vol. 95 (1961), pp. 235–50; P. W. Quade, "Temperatures over the United States in the Most Recent Years," unpublished master's thesis, University of Wisconsin, 1968; H. H. Lamb, *The Changing Climate* (London: Methuen & Co., Ltd., 1968); and R. G. Veryard, "A Review of Studies on Climatic Fluctuations during the Period of Meteorological Record," in *Changes of Climate, Arid Zone Research XX* (Liege, Belgium: United Nations Educational, Scientific, and Cultural Organization, 1963), pp. 3–16.

³ This principle has been illustrated in R. A. Bryson, "Air Masses, Streamlines, and the Boreal Forest," *Geographical Bulletin*, Vol. 8 (1966), pp. 234–41.

the frequency distribution of circulation patterns. A significant change in the frequency of a particular circulation pattern, or patterns, rearranges the air mass distribution and alters the mean temperature.

As knowledge of the atmospheric circulation increased during the first half of the twentieth century, it became apparent that an understanding of the behavior of the upper air circulation, as well as surface flow, was essential in the explanation of surface temperature patterns. The activity of the upper air westerlies, and especially the jet stream, is associated with the temperature patterns of the mid-latitudes.⁴ Changes in westerly wave patterns are closely followed by shifts in directions of air mass advection and in associated temperature anomaly patterns at the earth's surface. The major change in the hemispheric westerly wave patterns which occurred about 1950 is related to the hemispheric temperature trend and to the pattern of temperature change across the United States, North Atlantic Ocean, and western Europe.

NORTHERN HEMISPHERE TEMPERATURE

The mean temperature over the Northern Hemisphere increased about 0.6°C from 1890 to 1945 (Fig. 1), but from 1945 to the late 1960s it decreased by 0.3°C, and temperatures in the late 1960s approached those of 1900–1920. Over the last ten years the 1931–1960 average has been designated the current “normal” by the United States Weather Bureau when, in fact, the climate of this period is possibly the most abnormal within the last few hundred years.⁵

⁴ J. R. Harman, *Tropospheric Waves, Jet Streams, and United States Weather Patterns*, Commission on College Geography Resource Paper No. 11 (Washington, D.C.: Association of American Geographers, 1971), pp. 15–34; and W. H. Klein, *Application of Synoptic Climatology and Short-Range Numerical Prediction to Five-Day Forecasting*, U.S. Weather Bureau Research Paper No. 46 (Washington, D.C.: U.S. Department of Commerce, 1965), pp. 18–25 and 40–43.

⁵ Long-term plots of winter temperatures at New Haven, Connecticut, and at central and western European stations indicate that 1931–1960 is probably the most climatically anomalous period within the last few centuries. In addition, mean air temperatures inferred from Iceland sea ice records reached their highest value within the last 1,000 years during 1931–1960; W. M. Wendland, “Dating the Temporal Limits of Climatic Episodes during the Holocene,” unpub-

The representativeness of the mean temperature curve is open to question. Since the observation sites were mostly on land in the mid-latitudes, the curve probably best describes the temperature trend over the populated land masses.⁶ The effect of urbanization may, in part, be responsible for the temperature increase in the first half of the twentieth century.⁷ As a particular urban center grows in size, the “heat island” effect increases. The fact that many weather stations have been located in rapidly growing metropolitan centers emphasizes the importance of this factor. In addition, site relocations to cooler outlying areas may have contributed to the recent cooling trend.⁸ A large number of weather stations have been moved from the central city to airport areas since the end of World War II. Furthermore, changing procedures in the calculation of mean daily temperature may have affected the curve. In the nineteenth century the mean daily temperature was often computed as the average of three or four observations at regular hours throughout the day and night rather than the present average of the maximum and minimum.⁹ These factors could have produced an inhomogeneous or unrepresentative hemispheric temperature curve.

Nonetheless, many lines of evidence strongly suggest that the curve is representative. Temperature curves from nonurban areas, or for urbanized areas corrected for the heat island effect, are similar to their urban counterparts

lished doctoral dissertation, University of Wisconsin, 1972, p. 6.

⁶ See the map in J. M. Mitchell, Jr., “On the World-Wide Pattern of Secular Temperature Change,” in *Changes of Climate, Arid Zone Research XX* (Liege, Belgium: United Nations Educational, Scientific, and Cultural Organization, 1963), p. 164.

⁷ The effect of urbanization upon temperature trends in cities in the United States is discussed in J. M. Mitchell, Jr., “On the Causes of Instrumentally Observed Temperature Trends,” *Journal of Meteorology*, Vol. 10 (1953), pp. 244–61. Differences between urban and rural temperatures are summarized in J. T. Peterson, “Climate of the City,” in T. R. Detwyler, ed., *Man's Impact on Environment* (New York: McGraw-Hill, 1971), pp. 132–36.

⁸ In the 1940s and 1950s many official U.S. Weather Bureau stations were transferred from a downtown Post Office or Federal Building to a peripheral airport location.

⁹ The *World Weather Records* series designates the method in which daily mean temperatures have been calculated for various stations about the world.

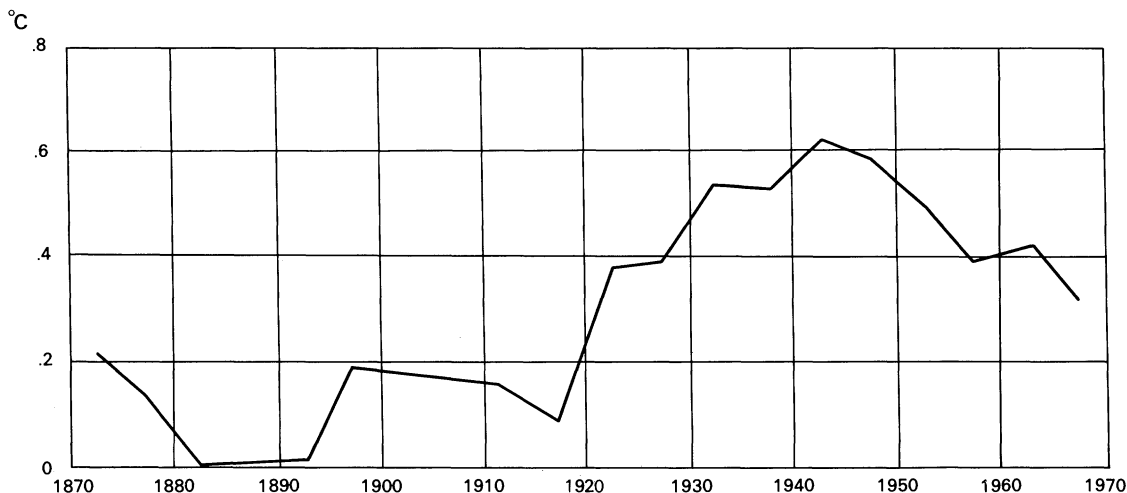


FIG. 1. Temperature change for the Northern Hemisphere. Values are pentad means expressed as deviations from the 1880–1884 pentad. The curve is from C. H. Reitan, "An Assessment of the Role of Volcanic Dust in Determining Modern Changes in the Temperature of the Northern Hemisphere," unpublished doctoral dissertation, University of Wisconsin, 1971, p. 4.

in direction and magnitude.¹⁰ The increase caused by urbanization probably is not sufficiently large to account for the mean temperature increase in the early twentieth century.¹¹ Evidence from glaciers also supports the validity of the hemispheric trend. Significant recession of mid-latitude mountain glaciers in the Northern Hemisphere was associated with the hemispheric warming, and some glacial advances have accompanied the recent cooling.¹² Furthermore, time series of the extent and/or duration of ice on lakes in the Upper Midwest, New England, and Scandinavia, and on the Baltic Sea and along the coast of Iceland are all in agreement with the hemispheric temperature trend.¹³

¹⁰ A graph in Mitchell, op. cit., footnote 7, p. 252, depicting New Haven, Connecticut, temperatures and the same temperatures corrected for the effect of urbanization illustrates that urbanization did not substantially change the overall "real" temperature trend. Winter temperature trends are similar at large urban centers and small communities a few tens of miles apart.

¹¹ See the discussion in Mitchell, op. cit., footnote 7, pp. 254–61, and, in particular, the chart at the bottom of p. 257.

¹² E. L. Ladurie, *Times of Feast, Times of Famine: A History of Climate Since the Year 1000* (Garden City, New York: Doubleday & Company, 1971), pp. 99–115.

¹³ My work on trends of ice extent and duration on lakes in the Upper Midwest, New England, and Scandinavia clearly indicates the relationship. Data

UNITED STATES TEMPERATURE

Examination of temperature trends in a number of cities in the eastern United States and of previous works concerning climatic change showed that the overall temperature trend in this region was similar to that of the hemispheric mean.¹⁴ The period 1931–1960 was a time of abnormal warmth, with significant cooling since the mid-1950s. Therefore, 1931–1960 was chosen as the base period, and data from 1961 through 1970 were compared with 1931–1960 "normals." The data consist of temperature deviations integrated over climatically homogeneous divisions within each state, with as many as ten climatic divisions in

for the Baltic Sea are from R. Jurva, "On the Variations and Changes of Freezing in the Baltic during the Last 120 Years," *Fennia*, Vol. 75 (1952), p. 23. Decadal averages of ice duration along the coast of Iceland are given in H. H. Lamb, "Climatic Fluctuations," in H. Flohn, ed., *General Climatology*, Volume 2 of *World Survey of Climatology* (Amsterdam, Netherlands: Elsevier Publishing Company, 1969), pp. 193–96.

¹⁴ T. J. Blasing, "Patterns of Climatic Anomaly over the Upper Midwest in Summer," unpublished master's thesis, University of Wisconsin, 1968, p. 42; Quade, op. cit., footnote 2, pp. 4–35; H. E. Landsberg, "Two Centuries of New England Climate," *Weatherwise*, Vol. 20, No. 2 (1967), pp. 52–57; and J. Namias, "Climatic Anomaly Over the United States during the 1960's," *Science*, Vol. 170 (November 13, 1970), p. 741.

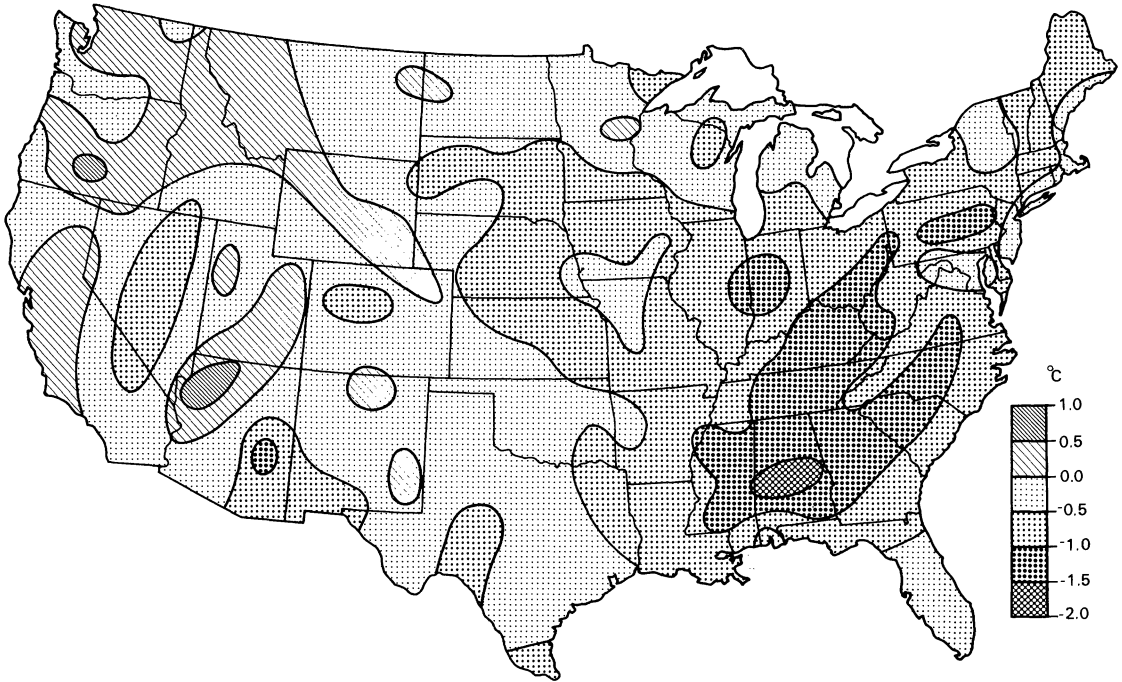


FIG. 2. Annual average temperature deviations, 1961–1970, from climatic normals, 1931–1960.

some states.¹⁵ Division averages are based upon all United States Weather Bureau stations and cooperative observers within the division. A division could have as few as five or as many as fifty observing stations. This method of using the state climatic divisions incorporates the whole population of observation sites, thereby avoiding some of the sampling errors which could occur if the data consisted of observations from a small number of stations scattered throughout the country.

Most of the United States had cooler mean temperatures in 1961–1970 than in 1931–1960 (Fig. 2). Almost all of the eastern United States averaged at least 0.5°C cooler. The area of maximum cooling extended from Indiana, Ohio, and Pennsylvania southward to Mississippi, Alabama, Georgia, and the Carolinas. Only portions of the Pacific Northwest, central California, Utah, and Arizona had higher mean temperatures in 1961–1970 than in 1931–1960. Summer and winter temperature deviations were similar to the annual temperature deviations, with an amplified pattern in winter

(Figs. 3 and 4). In winter, sections of the Pacific Northwest were actually 1°C or more warmer in 1961–1970 than in 1931–1960, whereas parts of the interior East and Southeast were at least 2°C cooler. In parts of the western United States the mean annual temperature change was opposite the hemispheric mean, but in the eastern United States the mean temperature decrease was generally much greater than in the Northern Hemisphere as a whole.

Magnitudes of cooling on the order of 1°C or 2°C in the eastern United States might seem relatively insignificant until their effects are observed in the behavior of sensitive climatic indicators. For example, about a 1°C decrease in mean winter temperatures was accompanied by an increase in the mean duration of ice on Houghton Pond, Massachusetts, from 86 days per winter in 1946–1955 to 102 days per winter in 1958–1967. On Lake Mendota, Wisconsin, a temperature change of similar magnitude resulted in a change in mean duration of ice per winter from 97 days in 1931–1940 to 112 days in 1956–1965. The 0.5°C temperature decrease from 1931–1960 to 1961–1970 in Madison, Wisconsin, was accompanied by an eight percent increase in number of heating degree days, an index associated with fuel consump-

¹⁵ These data are from *U. S. Climatological Data*, U.S. Department of Commerce, U.S. Weather Bureau, Vols. 67–76, 1961–1970.

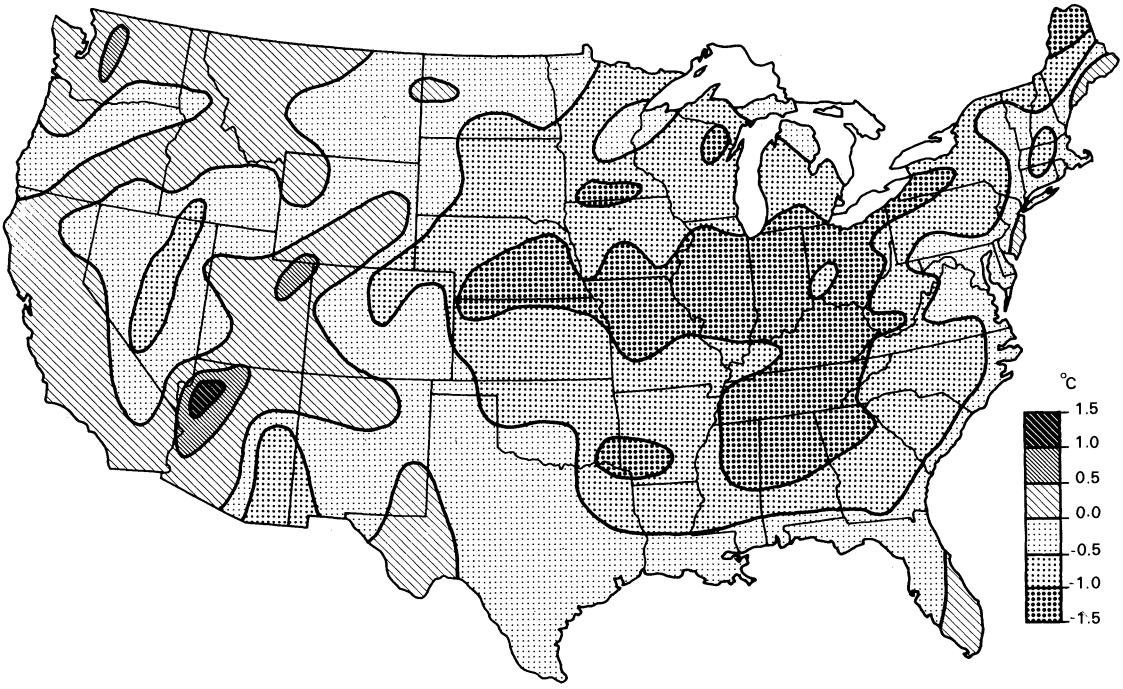


FIG. 3. Summer (July–August) temperature deviations, 1961–1970, from climatic normals, 1931–1960.

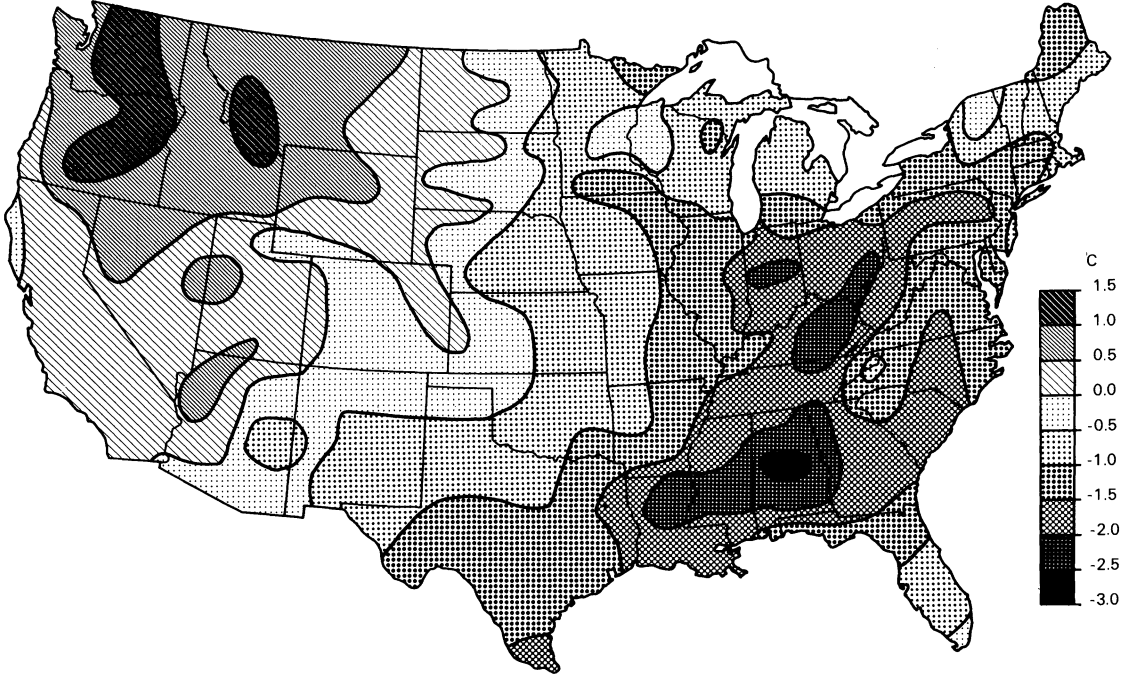


FIG. 4. Winter (January–March) temperature deviations, 1961–1970, from climatic normals, 1931–1960.

tion. The corresponding increase in heating degree days in the core area of maximum cooling was fifteen to twenty percent. These are only a few examples illustrating the large response which has occurred in sensitive indicators because of the recent cooling trend.

Temperatures in the United States in 1961–1970 have a marked similarity to those of the mid-nineteenth century.¹⁶ The eastern and central United States had negative anomalies in both periods, whereas portions of the West had positive anomalies. Current temperatures in the United States are approaching those which prevailed toward the end of the Neoboreal period (ca. 1550–1890).¹⁷

ATLANTIC OCEAN AND WESTERN EUROPE

Air temperatures in the western North Atlantic Ocean between 40° to 44°N latitude and 50° to 55°W longitude generally increased 1°–2°C from ca. 1910 until 1952–1954, and then sharply decreased 2°–3°C from 1952–1954 to 1959.¹⁸ Average annual sea surface temperatures southwest of a line from Spain to Greenland decreased 0.8°C during the 1950s, while northeast of that line there was an increase of 0.46°C.¹⁹ In 1962–1965 there were negative sea surface temperature anomalies as large as 3°C within an area of about 800,000 km² adjacent to the United States and Can-

ada.²⁰ Concurrently, sea ice off the coast of Iceland has increased from a mean frequency of 1.5 weeks per year in 1921–1950 to 4.0 weeks per year in the 1950s.²¹ Thus, in general, from 1950 into the 1960s temperatures in western portions of the North Atlantic Ocean have decreased, while small increases have been noted in eastern parts.

Temperature changes in western Europe, like those in the eastern United States, resemble the hemispheric trend. Mean annual temperatures in Norway increased at least 1°C from 1917 through 1940, but by 1950 the trend had reversed.²² Winter, summer, and mean annual temperatures in Great Britain were colder in 1961–1965 than in 1898–1960. The departures were statistically significant at the ninety-five percent confidence level. Winters averaged 1.5°C cooler, summers were 0.5°C cooler, and annual means 0.5°C colder during the most recent episode.²³ A subsequent study indicates that the cool episode continued through 1969.²⁴ The magnitude of the temperature change in Great Britain near 1960 was comparable to the change near 1890, but opposite in direction. About 1890 the Neoboreal ended and the period of warming from 1890 to 1950 began.

In general, a rather distinct temperature change has occurred since 1950 within the Northern Hemisphere from western North America to western Europe. Interspersed between regions of negative temperature change are smaller regions with positive temperature

¹⁶ E. W. Wahl and T. L. Lawson, "The Climate of the Midnineteenth Century United States Compared to the Current Normals," *Monthly Weather Review*, Vol. 98, No. 4 (1970), pp. 263–64.

¹⁷ Similarities between the climate of the late 1950s and 1960s and the nineteenth century have been noted by Wahl and Lawson, op. cit., footnote 16; Blasing, op. cit., footnote 14, pp. 40–42; and E. W. Wahl, "A Comparison of the Climate of the Eastern United States during the 1830's with the Current Normals," *Monthly Weather Review*, Vol. 96, No. 2 (1968), pp. 81–82.

¹⁸ P. R. Brown, "Climatic Fluctuation over the Oceans and in the Tropical Atlantic," in *Changes of Climate, Arid Zone Research XX* (Liege, Belgium: United Nations Educational, Scientific, and Cultural Organization, 1963), p. 110. The area discussed is about 650 km southeast of Newfoundland, and has an area of roughly 200,000 km².

¹⁹ M. Rodewald, "Sea Surface Temperatures of the North Atlantic Ocean during the Decade 1951–1960, Their Anomalies and Development in Relation to the Atmospheric Circulation," in *Changes of Climate, Arid Zone Research XX* (Liege, Belgium: United Nations Educational, Scientific, and Cultural Organization, 1963), p. 100.

²⁰ J. Namias, "Nature and Possible Causes of the Northeastern United States Drought during 1962–1965," *Monthly Weather Review*, Vol. 94, No. 9 (1966), pp. 550–51.

²¹ H. H. Lamb, *The Changing Climate* (London: Methuen & Co., Ltd., 1968), p. 197.

²² Veryard, op. cit., footnote 2, p. 5.

²³ H. H. Lamb, "Climate in the 1960's: Changes in the World's Wind Circulation Reflected in Prevailing Temperatures, Rainfall Patterns, and the Levels of the African Lakes," *Geographical Journal*, Vol. 132, No. 2 (1966), p. 194. Lamb compared a sixty-three year mean with a five year mean, and the two time periods may not be directly comparable since it is difficult to assess the variance of a time series only five years in length. If the variance of the sixty-three year period is sufficiently large, the probability that the five year period is a part of the same population as the sixty-three year period may be too large to "statistically accept" the difference between the periods.

²⁴ H. H. Lamb, "The New Look of Climatology," *Nature*, Vol. 223 (1969), p. 1210.

change. In particular, since 1950 the western third of the United States experienced warming, the eastern two-thirds of the United States and western North Atlantic Ocean underwent cooling, temperatures were higher in some sections of the eastern North Atlantic Ocean, and western Europe experienced cooling.

WESTERLY WAVE PATTERNS

According to the thermal wind relationship, the wind direction in the upper troposphere parallels the mean isotherms, with wind speed proportional to the temperature gradient and increasing with height. Lower temperatures occur on the poleward side of the upper air westerlies, higher temperatures on the equatorward side. The upper air westerlies are a continuous wind belt about the Northern Hemisphere within the mid-latitudes. They attain a maximum speed (i.e., the jet stream) where the horizontal temperature gradient is the greatest.²⁵ Because of their continuous character, changes in the westerlies in one sector of the hemisphere tend to alter the flow downstream.

The flow of the westerlies is generally latitudinal when the isotherm pattern is strongly west-east. This type of circulation is identified as "zonal" flow. When such flow occurs, cold air masses are restricted to high latitudes poleward of the jet stream and warm air masses are found equatorward. If the temperature gradient is not strictly south-north, however, and the isotherms bulge poleward and equatorward, the upper air westerlies have a wavelike pattern of flow, with two, three, four, or perhaps even more long waves positioned in areal association with the isotherms. There is a substantial amount of north-south flow, and this circulation pattern is termed "meridional." The portion of the wave which bulges equatorward is a trough. In the trough the pressure is relatively low aloft; thus, trough is synonymous with a relative upper air low. Northerly flow on the back side of a trough advects cold polar air masses, resulting in negative temperature anomalies. That portion of the wave which bulges poleward is a ridge of high pressure, or a relative upper air high. Temperature departures are positive in the ridge, in part because

the southerly flow on the west side of the ridge advects warm air masses.²⁶

If a particular wave pattern remains fixed for a long period of time, or if the wave pattern dominates the atmospheric circulation, its characteristic temperature anomaly will influence the climate.²⁷ A change in the prevailing wave pattern is accompanied by a change in the pattern of temperature anomalies. Such a change occurred about 1950.

CIRCULATION CHANGE

The recent categorization of the circulation patterns of the atmosphere over the Northern Hemisphere by Dzerdzeevskii has facilitated analysis of the upper air westerly wave pattern and identification of the circulation change.²⁸ Dzerdzeevskii used daily weather maps for the Northern Hemisphere since 1899 and hemispheric upper air data at the various pressure levels since World War II to classify hemispheric circulation into forty-one types, differing from each other in terms of locations and numbers of upper air westerly waves and directions of the major atmospheric currents over the various longitudinal sectors. He then identified the type which best fit the circulation on each day from January 1, 1899, through December 31, 1969.

Dzerdzeevskii's work is one of the first attempts at a classification of hemispheric circulation. Because of relationships between upper air westerly flow and tracks of surface cyclones and anticyclones, and between westerly flow and surface temperature anomalies, the upper air flow prior to World War II can be inferred with some degree of accuracy. Therefore, Dzerdzeevskii's circulation data are as homogeneous as possible in terms of present and past technology and the time period involved. A particular circulation type generally persists

²⁶ Climatic expression of mean long wave patterns in the upper air westerlies is discussed in Harman, *op. cit.*, footnote 4, pp. 15-17.

²⁷ Harman, *op. cit.*, footnote 4, p. 15.

²⁵ F. K. Hare, *The Restless Atmosphere* (New York: Harper & Row, 1963), pp. 56-57; *idem*, "The Westerlies," *Geographical Review*, Vol. 50 (1960), p. 350; and Harman, *op. cit.*, footnote 4, pp. 3-4.

²⁸ B. L. Dzerdzeevskii, *Circulation Mechanisms in the Atmosphere of the Northern Hemisphere in the Twentieth Century*, translated by R. Goedecke, edited by B. F. Berryman (Madison: University of Wisconsin Meteorology Department, 1971). Changing frequencies of Dzerdzeevskii's circulation types have been associated with drought patterns in the Great Plains, J. R. Borchert, "The Dust Bowl in the 1970s," *Annals*, Association of American Geographers, Vol. 61 (1971), pp. 5-10.

for several days, but the transition to another type often occurs in a few hours. Daily surface temperature records show similar abrupt transitions separating stable regimes.²⁹

Climatic changes may involve simultaneous changes in the frequency of several circulation types, and a factor analysis of time series of Dzerdzheevskii's types was used to identify such frequency changes. A covariance matrix was based upon associations in time among the forty-one variables. Those circulation types which occur in association with each other have relatively large covariances.

Empirical orthogonal functions, or eigenvectors, of the covariance matrix were calculated.³⁰ A particular eigenvector function identifies temporally and spatially related circulation types.³¹ The time series of the eigenvector scores, or relative frequency of the eigenvector function, has been used to identify

times of change in the hemispheric westerly wave pattern.³²

There are a number of possible types of time-series changes. A discontinuity occurs when the variable fluctuates about one mean value for a time, and then abruptly changes to fluctuate about another mean value. Bryson and Wendland argued that the climatic history of a region fits a step-function model which has numerous discontinuities.³³ Student's *t*-test was used to test for significant discontinuities within the time series of eigenvector scores.³⁴ A trend is a smooth monotonic increase or decrease in the average value of the variable. Trends might be expected in time series of eigenvectors of hemispheric circulation because the graph of hemispheric temperature change exhibits this behavior. Trends were described by regression analysis, and reversals of trends occurred at the intersections of two least-squares lines. Perhaps some time series are best described by higher order polynomials, but curvilinear relationships neither support the step-function model of climatic change nor resemble the Northern Hemisphere temperature curve. Lines of best fit, or mean values, and the dates of the changes are shown on the graphs of eigenvector scores.

The first eigenvector of summer circulation comprises types with meridional wave patterns (Fig. 5). Troughs are over eastern North America and western Europe, with frequent cold anticyclones and polar air masses in these regions. These types tend to occur more frequently in winter than in summer, and high frequencies of these types are accompanied by negative temperature departures near the troughs and winterlike circulation patterns about the hemisphere. Upper air ridges over the western United States and the central North Atlantic Ocean cause these regions to experience relatively warm air masses and positive temperature anomalies. Summers with a high

²⁹ Graphs of daily temperatures at many places in the mid-latitudes indicate rather stable weather episodes separated by abrupt transitions. These graphs often resemble a step function. The temperature fluctuates about a mean value for a number of days; then, following the passage of a frontal system and/or shift in the upper air westerly wave pattern, there is an abrupt transition to temperature fluctuations about another mean value associated with the post-frontal air mass and/or upper air westerly wave pattern.

³⁰ Eigenvectors represent characteristic combinations of the circulation patterns based upon covariances among time series of each pair of variables. The first eigenvector is that combination of anomalies of original variables which explains the most variance of circulation type frequencies over the time period considered. The second eigenvector explains less variance than the first, and the succeeding eigenvector functions explain continually decreasing amounts. There are as many eigenvector functions as the number of variables, but a few functions explain most of the total variability. This method efficiently minimizes the number of functions needed to explain a given portion of the variance. Eigenvector functions are unique to the data set. They are orthogonal, i.e., statistically uncorrelated with each other. The mathematical development of eigenvector analysis and its application in climatology are discussed in J. E. Kutzbach, "Empirical Eigenvectors of Sea Level Pressure, Temperature and Precipitation Complexes over North America," *Journal of Applied Meteorology*, Vol. 6 (1967), pp. 791-801; idem, "Large-Scale Features of Monthly Mean Northern Hemisphere Anomaly Maps of Sea-Level Pressure," *Monthly Weather Review*, Vol. 98, No. 9 (1970), pp. 708-16; J. M. Mitchell, Jr., ed., *Climatic Change*, Technical Note No. 79 (Geneva, Switzerland: World Meteorological Organization, 1966), pp. 72-75.

³¹ Mitchell, op. cit., footnote 30, p. 73; and Kutzbach (1967), op. cit., footnote 30, p. 791.

³² Kutzbach (1970), op. cit., footnote 30.

³³ R. A. Bryson and W. M. Wendland, "Tentative Climatic Patterns for Some Late Glacial and Post-Glacial Episodes in Central North America," in W. J. Mayer-Oakes, ed., *Life, Land, and Water* (Winnipeg: University of Manitoba Press, 1967), pp. 271-98.

³⁴ This test compares the differences between mean values of coefficients of different episodes within the time series. Episodes were considered samples from different populations if the calculated value of "*t*" was significant at the ninety-nine percent confidence level. This method is explained in Mitchell, op. cit., footnote 30, p. 63.

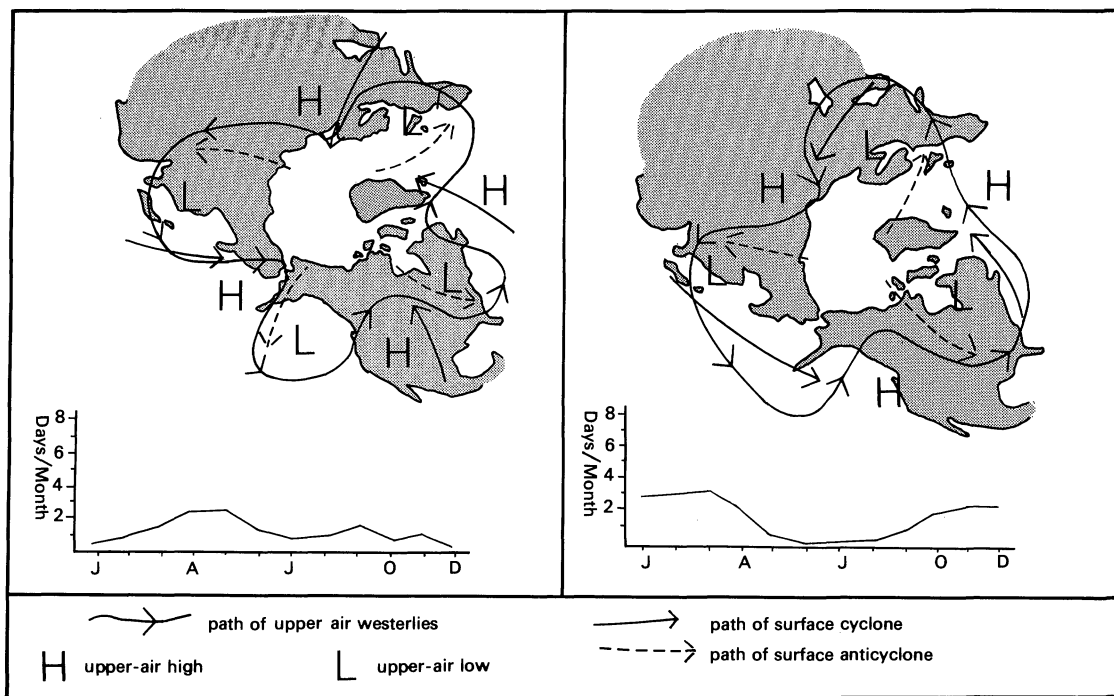


FIG. 5. Principal circulation types comprising the first eigenvector in summer, a composite of surface and upper air maps in Dzerdzevskii, op. cit., footnote 28. Wave patterns and locations of upper air highs and lows represent the 500-mb level. Graphs of monthly frequency of each type were derived from Dzerdzevskii's daily data and are mean values for 1899–1969.

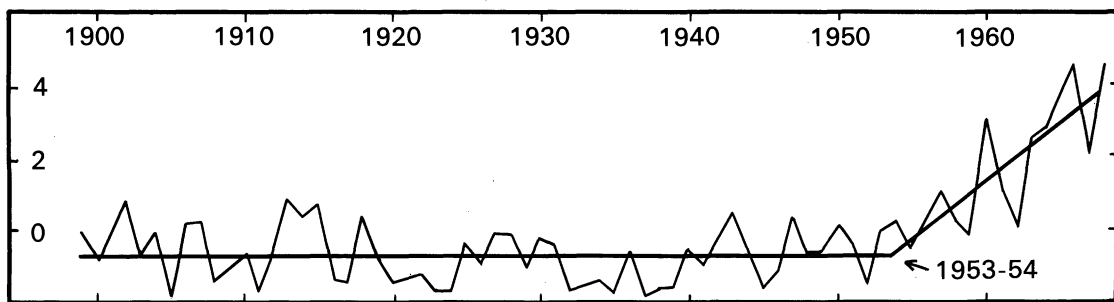


FIG. 6. Coefficients of the first eigenvector in summer. The numbers are eigenvector scores. A high positive number shows that the circulation types occurred frequently, and a high negative number shows they were absent. The heavy lines show mean values or significant trends. Time series plots of coefficients of eigenvector functions are discussed in Kutzbach (1970), op. cit., footnote 30, pp. 713–15.

frequency of this type of meridional circulation have a temperature regime similar to that which has occurred since 1950. This particular meridional circulation pattern occurred relatively infrequently until about 1950, but increased substantially thereafter (Fig. 6). The increase was marked enough to explain a large portion of the temperature change since 1950.³⁵

³⁵ Blasing, op. cit., footnote 14, p. 42, argued that increased northerly flow into the Upper Midwest since

The second eigenvector of summer circulation includes westerly wave patterns whose flow is relatively zonal (Fig. 7). Westerlies are confined to high latitudes, and there are no large troughs with associated cold air masses.

the early 1950s was associated with the cooling. H. H. Lamb, "Frequency of Weather Types," *Weather*, Vol. 20 (1965), pp. 9–12, related the recent cooling trend in Britain to more frequent northerly, northwesterly, and southerly circulation types in 1955–1964 than in 1916–1937.

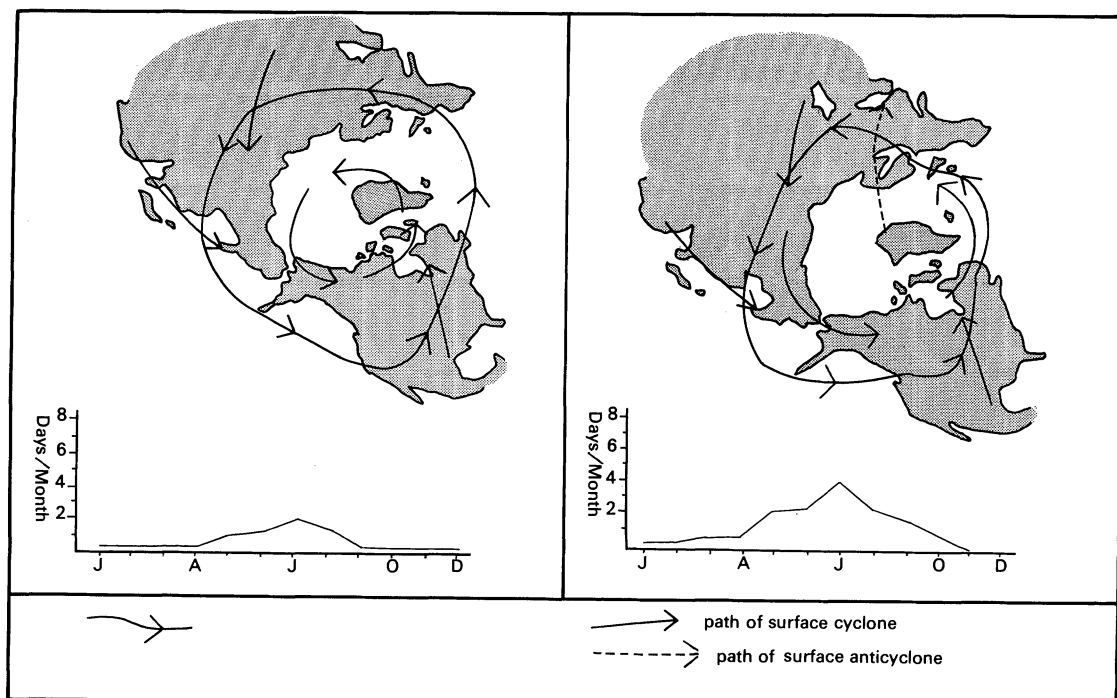


FIG. 7. Principal circulation types comprising the second eigenvector in summer.

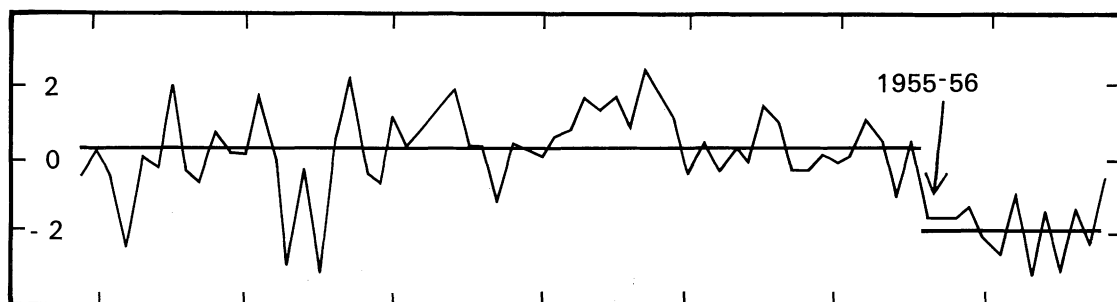


FIG. 8. Coefficients of the second eigenvector in summer; the lines represent significantly different means.

Such circulation types typically occur in summer. Western Europe and the eastern United States experience relatively warm air masses when they occur. This zonal circulation pattern was significantly less frequent in the late 1950s and 1960s than in 1900–1950, and the decreased frequency of zonal westerly flow since 1950 is associated with the trend toward cooler summers in the eastern United States and western Europe (Fig. 8). The time series of the coefficients of the second eigenvector resemble the step-function model of climatic change. The third and higher eigenvectors of summer circulation add little information concerning

summer circulation changes, and they do not warrant discussion.

The first eigenvector of winter circulation comprises types with meridional wave patterns (Fig. 9). Troughs are over eastern North America and western Europe, and ridges occur over western North America and the central North Atlantic Ocean. The westerly wave pattern is similar to that of the first eigenvector of summer circulation, and the types have characteristic winter season maximums. Temperature anomalies accompanying this westerly wave pattern are similar to those associated with the first summer eigenvector. Positive

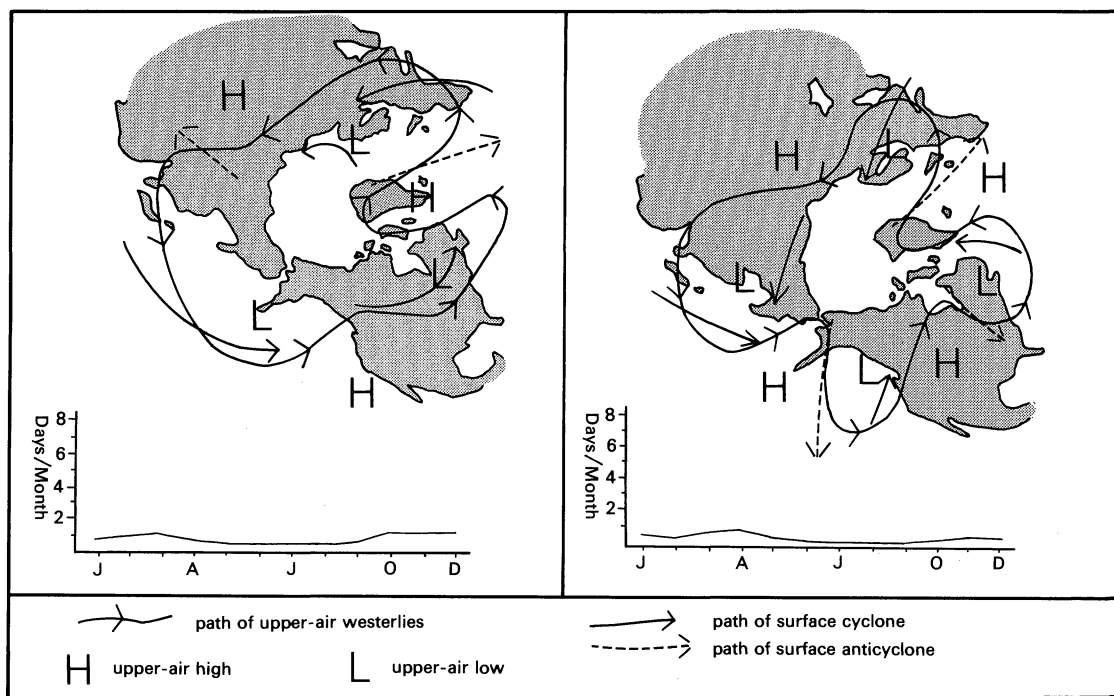


FIG. 9. Principal circulation types comprising the first eigenvector in winter.

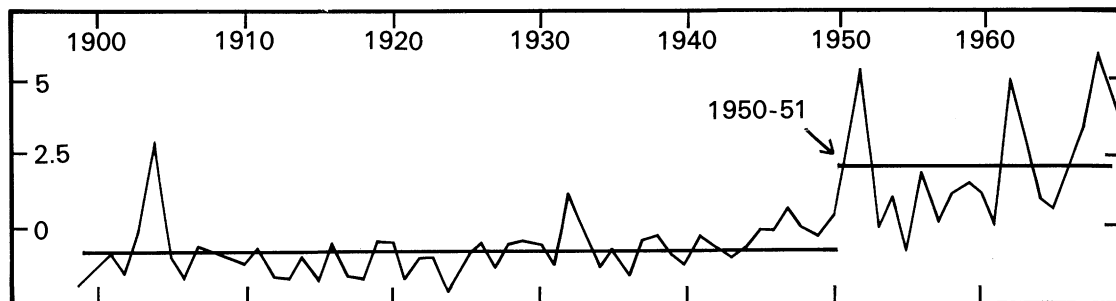


FIG. 10. Coefficients of the first eigenvector in winter; the lines represent significantly different means.

anomalies are associated with the ridges over the western United States and central North Atlantic Ocean, and the troughs over western Europe and the eastern United States have negative anomalies. This meridional wave pattern has occurred more frequently since 1950 than before (Fig. 10).

The second winter eigenvector includes westerly wave patterns with mean trough positions over Labrador, central Europe, and the east coast of Asia. Coefficients of this eigenvector exhibit no significant changes, but a large amount of fluctuation about one mean value.

The third winter eigenvector has the upper air westerlies confined to higher latitudes, and troughs occur less frequently over the eastern United States and western Europe (Fig. 11). Some of the types have summer season maximums. Western Europe and the eastern United States have high frequencies of relatively warm air masses when this type occurs. The decline in frequency of this type since the early 1950s is associated with the temperature changes that have occurred (Fig. 12). Additional winter eigenvectors contribute no significant information.

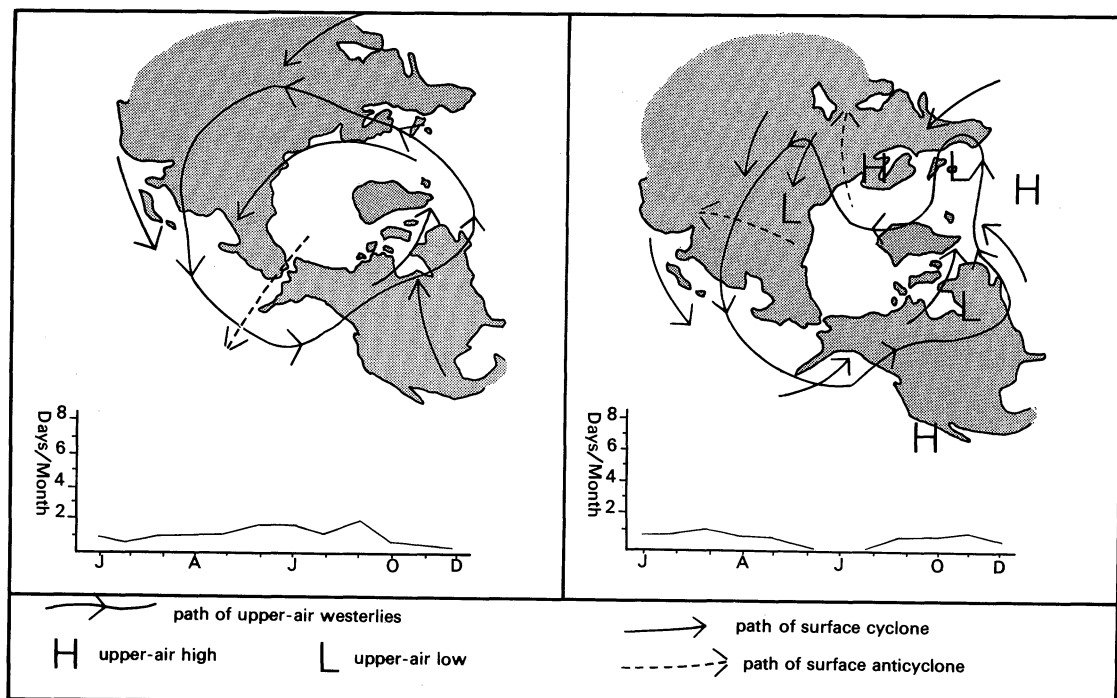


FIG. 11. Principal circulation types comprising the third eigenvector in winter.

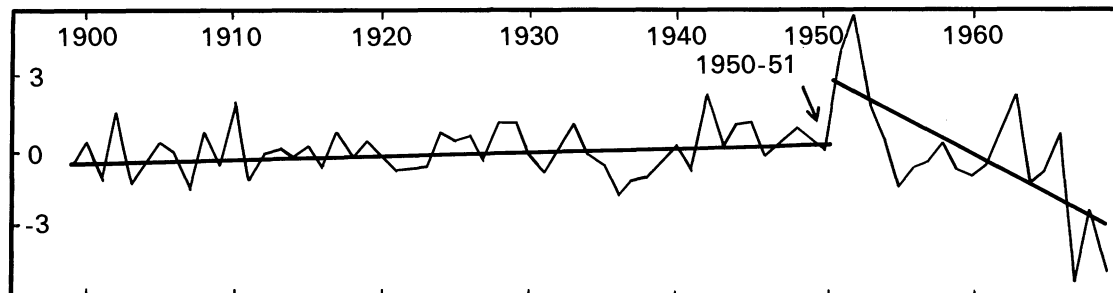


FIG. 12. Coefficients of the third eigenvector in winter; the lines represent mean values or trends.

In summary, meridional circulation patterns have become more prevalent in both winter and summer since the early 1950s, and zonal circulation patterns have occurred less frequently.³⁶ The prevailing westerly wave pat-

tern from about 1950 through 1969 consisted of relatively large troughs over eastern North America, western Europe, and the east coast of Asia, with ridges over western North America, the central North Atlantic Ocean, and western Siberia.

CONCLUSION

The trend of mean Northern Hemisphere temperatures changed significantly, from warming to cooling, around 1950. At about the same time the predominant hemispheric circulation flow changed from zonal to meridional. The regional response to increased meridional flow

³⁶ This concurs with Lamb, *op. cit.*, footnote 22, pp. 183, 194–196. Based on changes in frequencies of weather types over Great Britain and vicinity, the twentieth century was divided into two epochs in H. H. Lamb, *British Weather Types and a Register of the Daily Sequence of Circulation Patterns, 1861–1971*, Geophysical Memoirs No. 116 (London: Meteorological Office, 1972), pp. 11–15. From 1900 to 1954 westerly circulation was frequent, but from 1955 through 1971 blocking was prominent.

varied according to position in relation to the prevailing upper air westerly wave pattern. Temperatures cooled more than the hemispheric average near mean trough locations in the eastern United States and western Europe, but warming occurred near mean upper air

ridges over the western United States and the northeastern North Atlantic Ocean. The abrupt transition from a relatively stable zonal circulation before 1950 to a predominantly meridional circulation afterwards appears to support the step-function model of climatic change.